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STATISTICAL ANALYSIS OF SOLID PROPELLANT COMBUSTION.(U)

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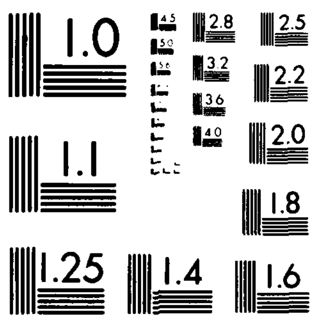

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Final Report

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STATISTICAL ANALYSIS OF SOLID PROPELLANT COMBUSTION

R. L. GLICK

University of Dayton
Research Institute
Dayton, Ohio 45469

October 1981

Final Report

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Department of the Air Force
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Studies were directed at direct measurement of the acoustic admittance of burning solid propellant with concurent pressure and optical anemometry measurements, internal ballistics of spin stabilized nozzleless rocket motors, and the application of Hilbert transforms to the computation of the imaginary part of the pressure coupled response from data for the real part. An optical anemometer based on an Argon ion laser and tracker electronics and a servo-positioned window strand burner based on a Princeton window burner were constructed. The servo-positioned strand burner operated successfully and

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Doppler burst phenomena were observed. However, tracker lock-on was not achieved. The spin stabilized nozzleless analysis showed that gas dynamic spin effects (as contrasted with acceleration induced burning rate changes) were small for tangential Mach numbers below 0.1. The Hilbert transform study showed that the imaginary part of the response function could be computed from the real part with acceptable accuracy for frequencies below one-third of the maximum frequency of the data.

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SECTION 1
INTRODUCTION

The design process employed with solid propellant rockets involves the analysis of quasi-steady performance, structural integrity, combustion stability, and cost for candidate designs. Performance and stability are analyzed with codes such as SPP[1] and SSP[2]. These codes require data on propellant properties and the motor geometry. Typically, the performance code (SPP) supplies the stability code (SSP) with the required grain geometry, the local burning rate, and the mean port flow. Therefore, if appropriate propellant parameters are available, these codes can evaluate both the performance (pressure- and thrust-time histories) and the propensity for instability (modal growth constants) of candidate designs.

The experimental determination of propellant parameters for the stability analysis is difficult, uncertain relative to velocity-coupled and distributed combustion driving, and expensive.[3] This situation and the need for these design data have led to a search for and development of improved diagnostics. Two direct measurement techniques have been examined: microwave interferometry[4] and optical anemometry.[5] The former seeks to measure the

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1. Nickerson, G. R., Coates, D. E., and Herman, R. W., "A Computer Program for the Prediction of Solid Propellant Rocket Motor Performance," AFRPL-TR-80-34, April 1981.

2. Lovine, R. L., "Standard Stability Prediction Method for Solid Rocket Motors," AFRPL-TR-76-32, May 1976.

3. Levine, J. N. and Andrepont, W. C., "Measurement Methods of Transient Combustion Response Characteristics of Solid Propellant-An Assessment," AIAA-79-1209.

4. Strand, L. D. and McNamara, R. P., "A Variable-Frequency Driver-Microwave Transient Regression Rate Measurement System," Experimental Diagnostics in Combustion of Solids, Progress in Astronautics and Aeronautics, Vol. 63, American Institute of Aeronautics and Astronautics, 1978, pp. 155-172.

5. Caveny, L. H., Collins, K. L., and Cheng, S. W., "Direct Measurement of Acoustic Admittance Using Laser Doppler Velocimetry," AIAA Journal 19, No. 7, July 1981, pp. 913-917.

thickness of the solid propellant instantaneously so that instantaneous burning rate and subsequently the response function can be computed from its temporal derivative. The latter seeks to measure the instantaneous gas velocity at the outer edge of the gas phase reaction zone, so that the acoustic admittance can be determined directly. From continuity the instantaneous gas velocity is related to the instantaneous burning rate by*

$$u_g \sim \rho_c r_b / \rho_g \ . \tag{1}$$

Since the order of magnitude of ρ_c/ρ_g is roughly 100, gas velocity fluctuations will be roughly two orders of magnitude larger than burning rate fluctuations. Moreover, thickness changes ΔL that must be measured by the interferometer are of magnitude $\hat{r}_b \Delta t$, where $\hat{r}_b$ is amplitude of the burning rate fluctuation, and Δt is the period of the oscillation. Now $\hat{r}_b \sim R_p \bar{r}_b \ (\hat{p}/\bar{p})$. Thus, the thickness change due to nonsteady burning in one cycle is

$$\Delta L \sim R_p \bar{r}_b (\hat{p}/\bar{p})/f. \tag{2}$$

From (1) and (2)

$$\hat{u}_g \sim R_p \bar{r}_b (\hat{p}/\bar{p}) \ \rho_c/\bar{\rho}_g. \tag{3}$$

---

* Continuity gives $\partial\rho/\partial t + \nabla \cdot \rho\vec{u} = 0$. Making gas velocity measurements near planes of symmetry reduces $\nabla \cdot \rho\vec{u}$ to $\partial\rho u/\partial\chi$; v, w, $\partial\rho v/\partial y$ and $\partial\rho w/\partial z$ are small because of symmetry. Consequently, continuity becomes $\partial\rho/\partial t + \partial\rho u/\partial\chi \sim 0$. Integrating and applying Liebnitz rule and the mean value theorem for integrals gives $\Delta\chi\partial\bar{\rho}/\partial t + u_g\rho_g - r_b\rho_c = 0$. For small oscillations and $\Delta\chi \sim 0$, (1) results.

Comparing (2) and (3) it is clear that the magnitude of the length perturbation that must be measured (ΔL) is at least two orders smaller than the magnitude of the velocity perturbation ($\hat{u}_g$); at 1000 Hz it is five orders of magnitude smaller. Moreover, the magnitude of ΔL decreases as frequency increases. For typical values ($R_p \sim 4$, $\bar{r}_b \sim 1$ cm/s, $\hat{p}/\bar{p} \sim 0.1$, $f \sim 1$ kHz, $\rho_c/\rho_g \sim 10^2$) $\Delta L \sim 4 \times 10^{-4}$ cm = 4μm and $\hat{u}_g \sim 40$ cm/s (the mean gas velocity is 100 cm/s). For 10 gH microwave signals the wavelength is roughly 3 cm. Thus, measurement of response functions at 1 kHz requires a phase measurement precision of the order of one part in 10^6 to reach one percent accuracy. This is at the limit of current technology. Consequently, microwave measurements in the 10 kHz frequency regime are doubtful. By contrast, velocity fluctuations on the order of 40 cm/s about a mean velocity of 100 cm/s to frequencies on the order of 10 kHz are well within the state of the art of optical anemometry. Accordingly, anemometry represents perhaps the best approach to high-frequency response function measurement.

The above discussion pertains to measurements that characterize the coupling of energy release to pressure oscillations in the first one millimeter or so from the burning surface. However, with some propellants (e.g., nitramines) the gas phase reactions are slower, so that the energy release is spread out over an appreciably longer distance (10^1 - 10^2 times larger). In these cases, distributed combustion driving must be considered. These situations are of current and future interest because nitramines will be the basis for min-smoke composite propellants. In these situations one also wants to know the way the quasi-steady energy release is distributed, so that it can be correlated with that fraction of the chemical energy release that is coupled to pressure oscillations. This correlation would permit quasi-steady calculations (available technology for CP grains[6]) to form the basis for computing distributed combustion driving.

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6. Beddini, R. A., "Reacting Turbulent Boundary Layer Approach to Solid Propellant Erosive Burning," AIAA Journal, 16, No. 9, Sept. 1978, pp. 898-905.

For quasi-steady flow along planes of symmetry, transverse variations and velocity components are small. Thus continuity leads to (1), which can be rewritten using the perfect gas law as

$$R_g T_g = p\, u_g / r_b \rho_c \quad . \tag{4}$$

Clearly, with concurrent pressure, gas velocity, and burning rate measurements $R_g T_g$ can be determined. In the absence of transverse gradients, the quasi-steady energy equation becomes

$$dH = \bar{c}_p dT_g + dQ_R + du_g^2/2 \approx 0 \ . \tag{5}$$

Thus, the local energy release is

$$dQ_R \approx -\bar{c}_p dT_g - du_g^2/2 \ , \ \frac{\partial}{\partial x} \frac{p\upsilon^3}{RT} = p\upsilon \frac{\upsilon^2}{RT} \ . \tag{6}$$

For ideal gases $c_p = R_g\, k/(k-1)$. Moreover, in the distributed energy release region k does not vary strongly. Therefore, with (4)

$$dQ_R \approx \frac{k}{k-1} d(pu_g)/r_b \rho_c - du_g^2/2 \ . \tag{7}$$

Once again, it is clear that local quasi-steady heat release can be measured with concurrent burning rate, pressure, and gas velocity measurements along the symmetrical stream tube. The variation of specific impulse and

characteristic velocity with characteristic length can be estimated[7] with $R_g T_g$ known as a function of distance (and time*) from the burning surface.

The mechanical energy equation[8] shows that the conversion of internal energy into mechanical energy is

$$dME/dt = p\ \vec{\nabla}\cdot\vec{u} \quad . \qquad (8)$$

Therefore, for a stream tube along planes with transverse symmetry the net mechanical energy added to the nonsteady field is

$$\overline{d(ME)'/dt} = \overline{p'\partial u'/\partial \chi} \quad . \qquad (9)$$

For a bulk mode oscillation as might occur in a strand burner this is

$$\overline{d(ME)'/dt} = \partial\overline{(p'u')}/\partial x \approx \left[\overline{p'u'(x+\Delta x)} - \overline{p'u'(x\mu}\right]/\Delta x \ .(10)$$

Thus distributed combustion driving can be measured by mapping out p'u' as a function of distance from the burning surface. This can be accomplished with simultaneous pressure and velocity measurements at either one location that is

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7. Williams, F. A., Barrere, M., and Huang, N. C., Fundamental Aspects of Solid Propellant Rockets, AGARDograph 116, October 1969, pp. 173-177.

8. Bird, R. B., Stewart, W. E., and Lightfoal, E. N., Transport Phenomena, (John Wiley and Sons, New York, 1960) pp. 81-82.

* time $= \int_0^x u_g^{-1}\, d\chi$.

slowly traversed relative to the burning surface* or at two closely spaced locations that are slowly traversed relative to the burning surface.* Concurrent pressure and velocity measurements may also be employed to determine the distributed combustion driving.

In summary, it is seen that concurrent pressure, burning rate, and gas velocity measurements in the core region of a strand plume can be employed to determine the following:

- acoustic admittance of the burning surface,
- local temperature,
- local energy release,
- local distributed combustion driving, and
- specific impulse and characteristic velocity and their variation with residence time.

The fact that these measurements can be made concurrently, with reasonable precision, and to frequencies in the 10 kHz domain indicates that the optical anemometry approach offers appreciable diagnostic advantages relative to other methods.[3]

Caveny, Collins, and Cheng[5] showed that direct measurements of the acoustic admittance of a burning propellant surface are feasible with optical anemometry. However, these measurements were performed with reasonably short strands (~ 5 cm). To achieve increased accuracy and the potential for acquiring other data, a longer burn time is required. This program was primarily aimed at repeating the Caveny, et. al. experiments with a longer burn time.

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* For sinusoidal oscillations this might be accomplished with a lock-on amplifier (p' employed as reference) having an appropriate time constant.

SECTION 2
ACCOMPLISHMENTS

Progress has been made in the following areas:

- construction and demonstration of a servopositioned strand burner capable of burning 1/4 x 1/4 x 8 in. strands,
- construction of an optical anemometer using an argon ion laser and tracker electronics,
- analysis of the effects of spin on the idealized performance of nozzleless rocket motors,
- interpretation of spontaneous transitions to nonlinear instability in forced longitudinal wave motor tests, and
- application of Hilbert transforms to the computation of the imaginary part of the pressure-coupled response function from the real part in general situations.

The first two items are the major component parts of apparatus for the direct measurement of acoustic admittance of burning solid propellant.

Servopositioned Strand Burner

A standard optical strand burner, digital stepping motor, and electronic control system were obtained from Princeton University. These items were incorporated into a servopositioned strand burner capable of burning 1/4 x 1/4 in. strands up to eight inches long. The design of this apparatus is described in a technical note submitted for publication to *The Journal of Spacecraft and Rockets*.

Optical Anemometer

A single-channel Laser Doppler Velocimeter (LDV) system was assembled. Most of this equipment was furnished by the University of Dayton Research Institute (UDRI) for this program. The LDV system includes a CW argon ion laser and a TSI 1090-1A tracker. Successful trials of this system have been run in the burner geometry (including windows) using both a calibration wheel and smoke as a target. Initial checks on propellant flames suffered from

insufficient signal-to-noise ratio for useful results. It is believed that the system has now been improved to the point where success with propellant strands may be anticipated.

Schlieren and Shadow Photography of Burning Rocket Propellant

Several attempts were made to record schlieren photographs and shadowgraphs of the gases evolved by a 6-mm square by 50-mm long section of rocket propellant ignited at one end. A pulsed metal vapor laser producing 20-ns wide pulses of light was used as an illuminating source. The laser was fired by a triggering system arranged so that it fired synchronously with the motion of the frames on a 16-mm Fastax camera. Kodak RAR 2496 film in 125-foot rolls was used as the recording medium. The Fastax camera was capable of reaching framing rates of 8 kHz near the end of the roll.

The light from the laser was focused onto a pinhole, collimated by a lens, and passed around the sample. The light was condensed by a second lens onto the film. The object to image size ratio was approximately 3:1. The maximum film velocity in the camera was 60 m/s. Since the exposure time was only 20 ns, no motion-compensation prism was used in the camera because, with such a short exposure time, the maximum blur of the image was only 1.2 μm, far below the resolution limit of any 16-mm film. The sample was ignited and the camera started a short time later, because the rate at which the fuel was consumed was very slow compared to the framing rate of the camera.

In general, shadowgraphs are capable of defining the boundary between two volumes of gas having different indices of refraction, but they fail to yield quantitative information because the fringes observed depend upon the second derivative of this index. They are useful, however, because of their sharp definition of boundaries. Schlieren photographs are more quantitative because their fringes depend upon the integrated optical path length through the sample. Regardless of the fact that the beam stop in a schlieren system eliminates a considerable amount of the light passing around and through the sample, both types of photographs can be recorded with the same amount of laser light.

Successful schlieren and shadow movies were recorded, despite the brilliance of the flame produced by the combusting fuel. It was found that it

was not necessary to eliminate the yellow light produced by the fuel (although this could have been accomplished easily by the use of an optical filter) because the brightness of the laser was so much greater than that of the flame. In general, the quality of the films produced was poor. The volume of gas produced by the fuel was very large and it spread far beyond the three-inch diameter viewing area that was available. The fuel burned slowly on the time scale of the photographs. Therefore, future attempts to record the evolved gases on a global scale should be performed at a lower framing rate, perhaps as slow as 1 kHz. Two experimental difficulties led to the poor quality of the photographs recorded: (1) in the case of the shadowgraphs, the system sensitivity was simply too high and (2) for the process of recording the schlieren photographs, a satisfactory beam stop was not available.

In subsequent work on other combusting systems, these deficiencies were rectified but could not be applied to the photography of the solid rocket propellant. The sensitivity of a shadowgraph depends on the percentage of the light deflected by the subject which is allowed to reach the film and upon the degree to which the subject is in focus. Because of the large size of the gas cloud from the fuel, it is impossible to have the entire cloud in focus at one time, so the sensitivity of the shadowgraphs must be reduced by the insertion of a stop in the focal plane of the camera lens to limit the amount of off-axis light reaching the film. Such an aperture was not available when the fuel photographs were taken. The problem associated with the schlieren photography was created by the use of coherent laser light whose diffraction and interference properties at a sharp beam stop edge are different from those of incoherent light. The combusting rocket fuel was the first example of the severe gradients present in a harsh flame.

The experience gained from the attempts to photograph this system was useful in subsequent schlieren and shadow photography performed on two combustors in the Aero-Propulsion Laboratory at Wright-Patterson Air Force Base.

Spin Stabilized Nozzleless Rocket Motors

An integral method analysis was completed for the effects of spin on the idealized performance of nozzleless rocket motors. Results show negligible effects for tangential Mach numbers (tangential velocity of burning

surface/acoustic speed) below 0.1. An article describing this work has been submitted for publication to the forthcoming AIAA Joint Propulsion Conference.

Spontaneous Transition to Nonlinear Instability in Forced Longitudinal Wave Motor Experiments

Literature concerning transition to nonlinear instability, acoustic erosivity, erosive burning, and cold flow studies was combined with FLW motor results to explain the cross sectional geometry dependence of the transitional phenomena. The results of this "inter-group study" were reported to the AIAA/SAE/ASME Joint Propulsion Conference in July 1981.

Application of Hilbert Transforms to Response Function Data

Pressure-coupled response function data obtained from T- and rotating valve burners are constrained to the real part. However, knowledge of the sign of the imaginary part is very useful for design purposes; it can be employed to determine the sign of the velocity-coupled driving contribution. However, no general methodology was known to predict the imaginary part from the real part. The applicability of Hilbert transform relations to this task was explored. The results of this study were submitted for publication to the forthcoming AIAA Joint Propulsion Conference.

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1. Glick, R. L., Micci, M. M. and Caveny, L. H., Transition to Nonlinear Instability in Solid Propellant Rocket Motors, AIAA-81-1520.

2. Glick, R. L., Lincks, D. R., and Yerushalmi, S., "Servopositioned Strand Burner," submitted to The Journal of Spacecraft and Rockets for publication, January 1982.

3. Yerushalmi, S. and Glick, R. L., "On the Internal Ballistics of Spin Stabilized Nozzleless Rocket Motors," submitted for publication to the 1982 AIAA Joint Propulsion Conference, December 1981.

4. Becker, R. J. and Glick, R. L., "Application of Hilbert Transforms to Response Function Data," submitted for publication to the 1982 AIAA Joint Propulsion Conference, December 1981.

NOMENCLATURE

c_p	specific heat at constant pressure
f	frequency
dH	total enthalpy change
k	specific heat ratio
ΔL	strand length change during one oscillation due to nonsteady burning
ME	mechanical energy
p	pressure
dQ_R	heat release from chemical reaction
r_b	burning rate
R_g	gas constant
R_p	pressure-coupled response function
t	time
T_g	gas temperature
u_g	gas velocity normal to burning surface
u	gas velocity
x	distance from burning surface
ρ_c	propellant density
ρ_g	gas density
$(\ )'$	denotes a fluctuating term
$\overline{(\ )}$	denotes a mean
$\hat{(\ )}$	denotes an amplitude

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